EXPERIMENTAL INVESTIGATION

OF

THE EFFECT OF AN ELECTRIC FIELD ON THE VISCOSITY

OF LIQUIDS

Thesis by

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SUMMARY

A new type viscosimeter is described which enables the viscosity of any liquid to be measured while it is in an electric field. The electric field was found to increase the viscosity of all liquids with dipole moments, while the liquids without moments in general showed no effect. It was found that the change in viscosity varies with the shearing stresses to which the liquid is subjected. A qualitative theory is proposed which agrees very well with the results found experimentally.

INTRODUCTION

The effect of an electric field on the viscosity of liquids has been investigated only in very recent years. After a search of the literature I have found only two papers[5)6)] on the subject both by the same authors. The first paper was a short note on the influence of an electric field on the flow of liquids through glass capillaries. In this method the electrostriction of the glass due to the field was large compared to the effect on the liquid. They determined the electrostriction of the glass by a method which gave them a large experimental error. Hence the results published in this paper were erratic and probably worthless (see Table I). A second paper published recently by the same authors describes a new method for the determination of the change in the viscosity with an electric field. Their method was similar to one that I used in 1933. The liquid flows between two flat metal electrodes which are separated by glass spacers forming a rectangular channel. The above paper was very brief and gave only a description of their apparatus without mentioning any of the dimensions. In the early type of apparatus that I used the gap between the plates amounted to .3 mm. The liquid which I used at that time was sesame oil. The results of the experiment were positive. I found that the viscosity was increased by about 3% shortly after the field was turned on. If the field were left on for two or three hours the

effect increased. The maximum observed increase in the viscosity was 15%. After the field was turned off the viscosity returned to the same value regardless of the amount of time the field had been on. Sesame oil was an unfortunate choice for a liquid since it is a highly complicated organic substance and not a homogeneous liquid. My explanation for the observed data is that some part of the oil was electrolizing out of solution and sticking to one of the walls while the field was on. This would explain the gradual increase in the effect with time and, since whatever was coming out of solution would cease to stick to the wall when the field was turned off, it would explain the return of the viscosity to normal as soon as the field was turned off. Herzog and Kudar's results are given in Tables I and II. My criticism of these results is as follows: a) no attempt is made to get a uniform velocity gradient; b) the oil being constantly renewed in the gap, there is no means of telling whether or not the temperature of the oil remains the same when the field is on as it is when there is no field. In my opinion the following conditions must be imposed upon the experiment:

1) The same oil must be used to measure the viscosity, both with and without the field.
2) The velocity gradient must be the same throughout the liquid.

3) The gap across which the field is applied to the liquid must be very large compared to molecular diameters.

4) The method of measuring the viscosity should be rapid so that there is no chance for conditions to change between readings.

TABLE I

	Substanz	Durchflusszeit vor Anlegen des Feldes Sec.	Proz. Änderung der Durchflusszeit im Feld %	Proz. Änderung nach Ausschaltung der Spannung %	Messfehler in %
1.	Hexan	279,0	0,25	0,04	0,06
2.	Undekan	811,4	0,14	0,01	0,02
3.	Cyclohexan	562,4	0,12	0,07	0,01
4.	Athylijodid	178,0	0,17	0,11	0,04
5.	Heptylbromid	609,0	0,18	0,07	0,02
6.	Methylenchlorid	169,9	0,18	0,00	0,06
7.	Methylenjodid	443,7	0,25	0,14	0,04
8.	Chloroform	216,4	- 0,60	0,00	0,05
9.	Pentachloräthan	721,3	- 0,40	0,12	0,04
10.	Tuluol	380,2	0,26	0,13	0,01
11.	o-Xylol	506,8	0,26	0,06	0,03
12.	Chlorbenzol	377,0	- 0,50	0,05	0,02
13.	o-Chlortoluol	506,1	- 1,11	0,09	0,05
14.	m-Chlortoluol	408,3	0,49	0,12	0,07
15.	p-Chlortoluol	439,4	- 0,98	0,11	0,04
16.	o-Dichlorbenzol	555,2	1,62	0,11	0,06
17.	m-Dichlorbenzol	439,2	- 0,84	0,09	0,06

From Electrostatic effect on viscosity of fluids.

Herzog, Kudar, Paersch

Naturwissenschaften Sept. 8, 1933 pp. 662

TABLE II

		ohne Spannung	mit 110 V. Spannung		
1.	Hexan	164,4 (0,1)	164,4 (0,1)		
2.	Zyklohexan	407,2 (0,3)	407,5 (0,2)		
3.	Tetrachlorkohlenstoff	204,0 (0,2)	204,0 (0,2)		
4.	Chloroform	130,4 (0,1)	136,6 (0,2)		
5.	Pentachlorathan	447,5 (0,1)	448,2	448,8	
6.	Trimethylenchlorid	284,2 (0,1)	290,2	290,8	durchschnittlich je 5 Versuche
7.	Trimethylenbromid	336,2 (0,3)	336,7	338,2	
8.	Diäthyläther	115,8 (0,1)	138,5	134,5	
9.	Dibutyläther	304,5 (0,1)	306,1	305,3	
10.	Orthodichlorbenzol	345,6 (0,2)	347,1	348,9	
11.	Äthyljodid	106,1 (0,1)	124,2 (0,3)		
12.	Butyljodid	183,9 (0,1)	183,6 (0,2)		
13.	Decyljodid	844,4 (1,7)	844,6 (1,6)		

From Electrostatic effect on viscosity of fluids

Herzog, Kudar, Paersch

P. Z. 35 June 1, 1934 p. 446

DESCRIPTION OF APPARATUS

In addition to the four conditions mentioned in the introduction to this thesis, I imposed the condition that the amount of liquid required to operate the apparatus be small. With these conditions in mind, I designed an apparatus of the rotating concentric cylinder type. This type of apparatus has been used extensively for the measurement of relative viscosities by Couette, Hatschek, Leroux, Gilchrist and Harrington. Gilchrist and Harrington were the first to successfully use this type of apparatus for the measurement of absolute viscosity. Let us consider the theory of this type of apparatus before describing the instrumental details.

If we have two cylinders rotating with an angular velocity Ω in a viscous fluid the moment per unit length at any point is given by

$$M = 2\pi r \tau_x r$$

$$\tau = \frac{M}{2\pi r^2}$$

also in rotational motion we know that

$$\tau = \mu r \frac{d}{dr}\left(\frac{W}{r}\right)$$

where μ is the coefficient of viscosity and W is the tangential velocity of the liquid.

Two dimensional flow is assumed.

Equating

$$\frac{M}{2\pi r^2} = \mu r \frac{d}{dr}\left(\frac{W}{r}\right)$$

$$\frac{d}{dr}\left(\frac{W}{r}\right) = \frac{M}{2\pi\mu r^3}$$

$$\frac{W}{r} = -\frac{M}{4\pi\mu r^2} + A \qquad 1)$$

If we now impose the boundary conditions that at r = a, the angular velocity is zero, while at r = b the angular velocity is Ω

$$\frac{W}{a} = 0 = -\frac{M}{4\pi\mu a^2} + A \qquad 2)$$

$$\frac{W}{b} = \Omega = -\frac{M}{4\pi\mu b^2} + A \qquad 3)$$

Subtracting 2) from 3) we have

$$\Omega = \frac{M}{4\pi\mu}\left(\frac{1}{a^2} - \frac{1}{b^2}\right) = \frac{M}{4\pi\mu}\left(\frac{b^2 - a^2}{a^2 b^2}\right)$$

or

$$M = \frac{4\pi\mu\Omega a^2 b^2}{b^2 - a^2} \qquad 4)$$

if we now substitute for Ω in terms of R.P.M.

$$M = \frac{8\pi^2\mu N a^2 b^2}{b^2 - a^2} \qquad 5)$$

VISCOSIMETER

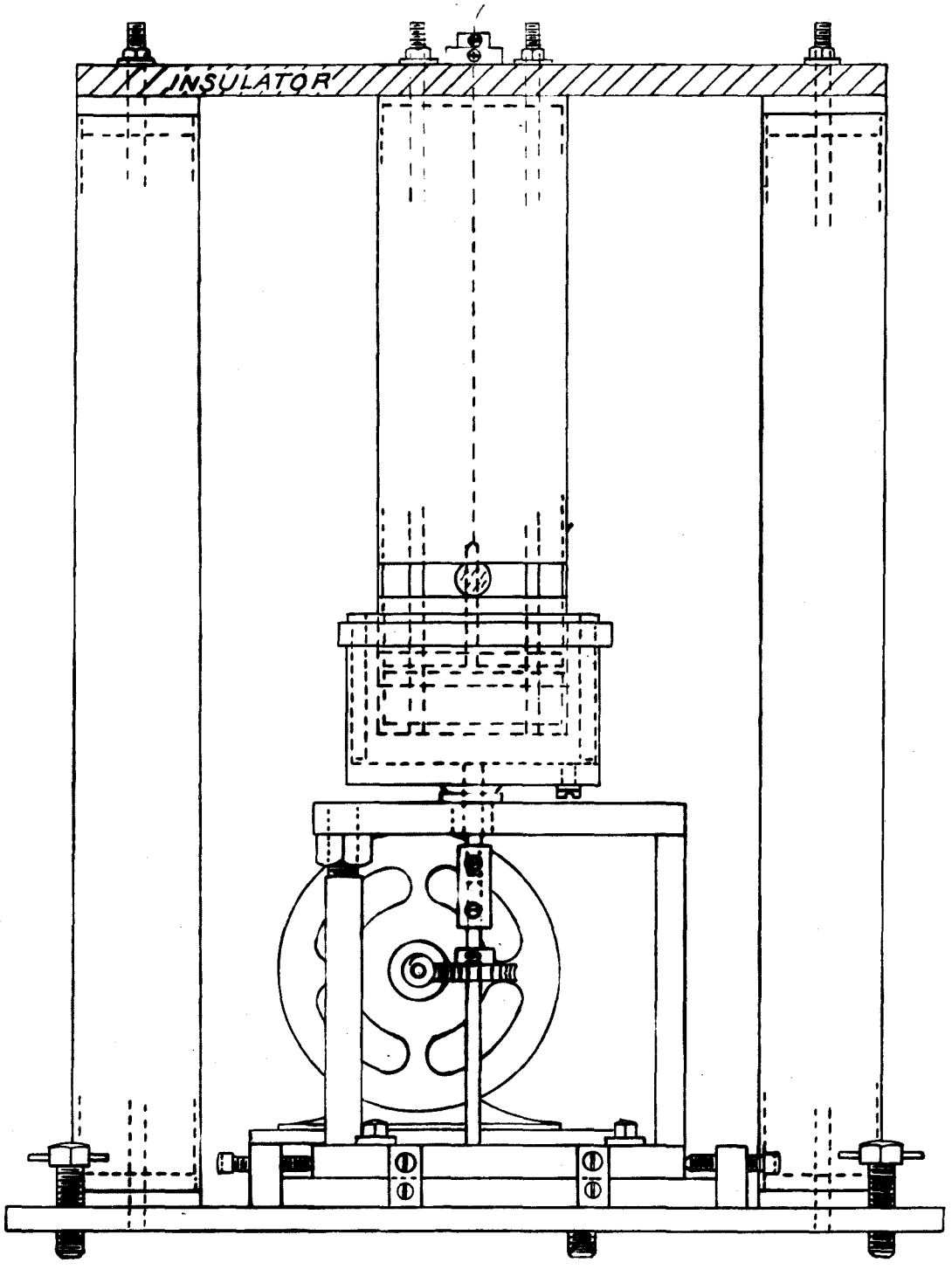


Fig. 1

3/8 Actual Size

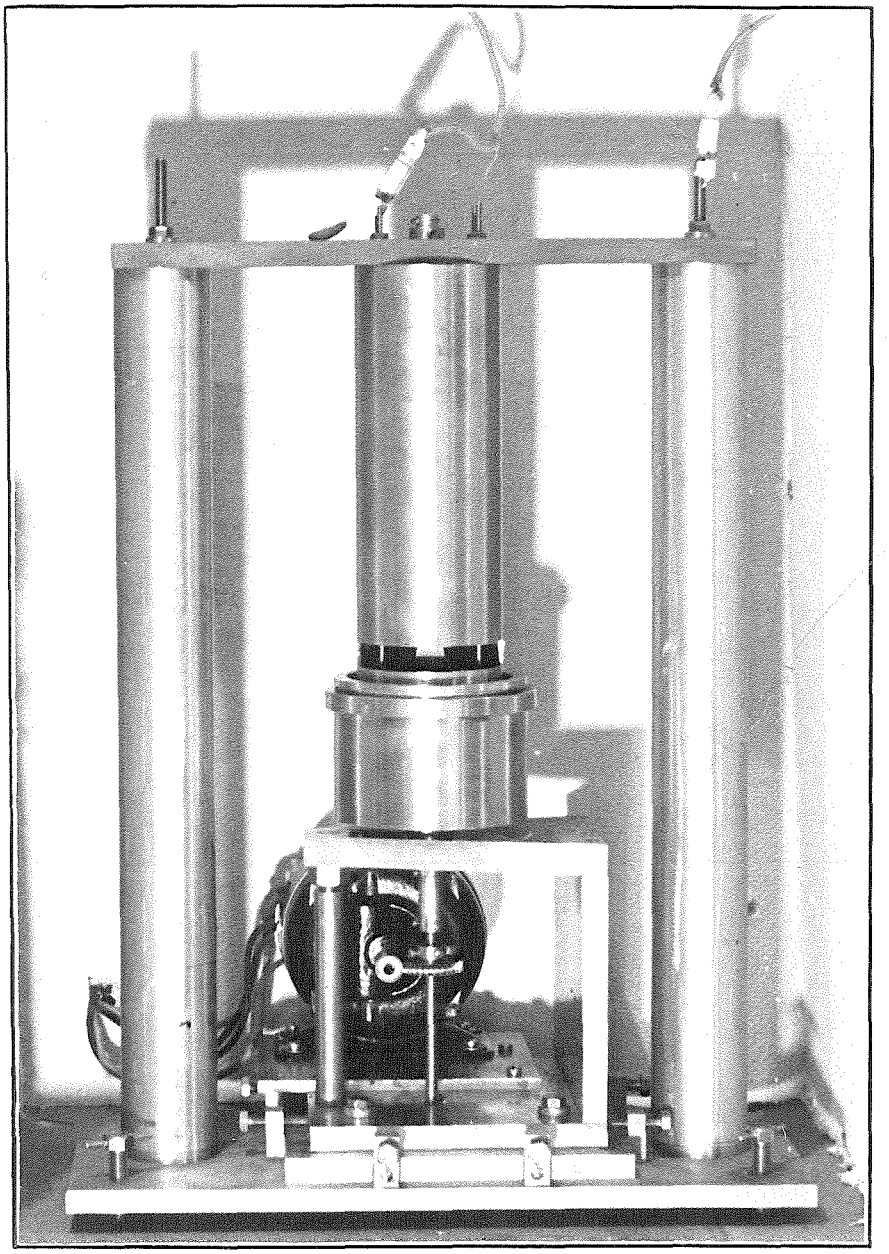


Fig. 2

View of Complete Instrument

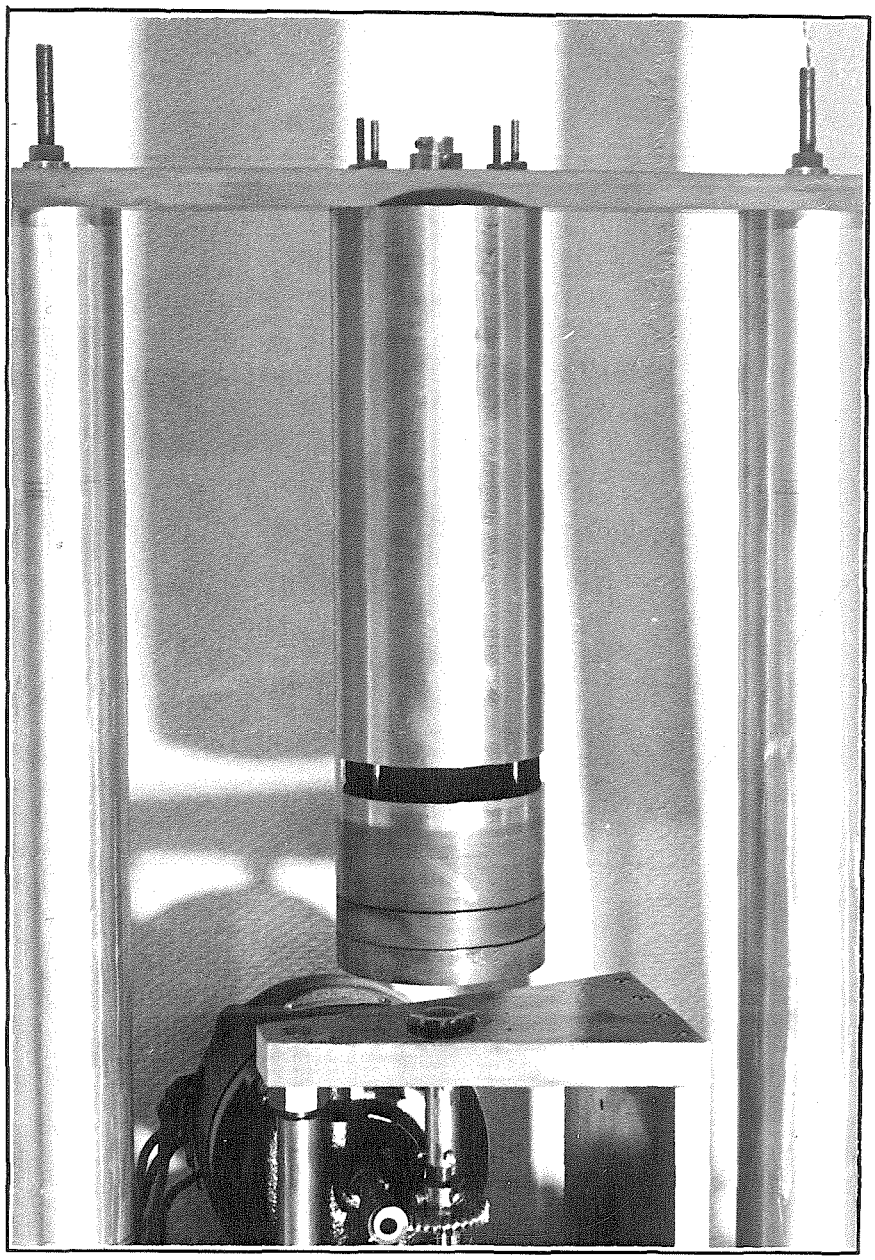


Fig. 3

View of Instrument with Outer Cylinder Removed

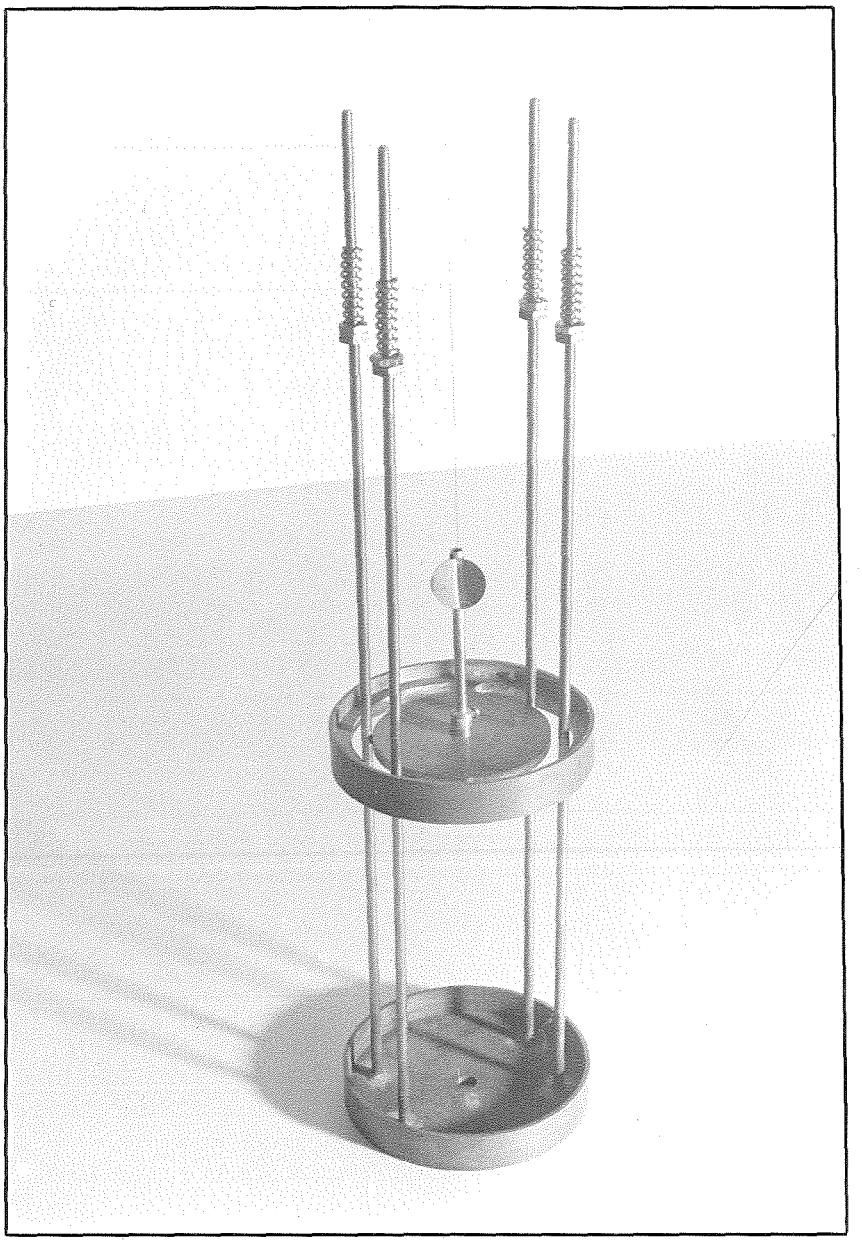


Fig. 4

View Showing Suspension, Lower Guard
Cylinder and Supports

Now the angular velocity gradient at any point in the liquid is given by

$$\frac{dW}{dr} = \frac{M}{4\pi\mu r^2} + A \qquad 6)$$

Now from equation 2) we have

$$A = \frac{M}{4\pi\mu a^2}$$

$$\therefore \frac{dW}{dr} = \frac{M}{4\pi\mu}\left(\frac{1}{r^2} - \frac{1}{a^2}\right) \qquad 7)$$

In this type of apparatus then, we would expect the couple exerted on the inner cylinder by the liquid to be directly proportional to the R.P.M. of the outer cylinder. A scale drawing of the viscosimeter is given in Fig. 1. Fig. 2, Fig. 3 and Fig. 4 show different views of the completed instrument. The suspension (see Fig. 4) consists of a section of a cylinder 1 cm. high and 3.8 cm. in radius. Inside the cylindrical ring is a horizontal disc pierced by two semicircular slots. The vertical shaft upon which the mirror is mounted is attached to the center of the disc. The purpose of this shaft is to raise the level of the mirror so that it can be observed over the top of the outer cylinder and still be rigidly attached to the suspension. The suspension wire, .01 inches in diameter, runs through the center of the vertical shaft and is clamped by means of a set screw at the bottom of the

shaft, thus using the maximum length of wire. Guard cylinders are mounted above and below the suspension to insure uniformity of the electric field and of the liquid flow. The lower guard cylinder is approximately 1 cm. high and is closed on the bottom with the exception of a small drain hole. When the liquid is in the apparatus, it comes up inside of the suspension and guard cylinders. The liquid inside the guard cylinders, however, remains at rest since the torque exerted on it through the drain hole and the slits between the suspension and guard cylinders, by the liquid in motion outside, is exceedingly small. This inner liquid also assists in damping out the oscillations of the suspension. The lower guard cylinder is held in place by means of four rods which go through the semicircular slits in the suspension and fasten to the top support. The upper guard cylinder is immersed approximately 1 cm. in the liquid when the apparatus is filled. The upper guard cylinder has a slit in it through which the deflections of the mirror and hence the suspension can be observed by means of a telescope and a scale. The outer cylinder has a radius of 2 inches and is fitted with a liner which reduces the gap between the suspension and liner to approximately .5 cm. The outer cylinder was made from brass tubing and since it is extremely difficult to machine this, it is not truly cylindrical, being out of round by about .005 inches.

This eccentricity is sufficient to cause an oscillation of the suspension. The liner was turned out of solid brass, hence it is accurately true and causes no oscillation of the suspension when rotating. The apparatus was used with the liner in place in taking all of the data presented in this thesis. The whole suspension system is mounted on an insulating fiber material and has been tested up to 7000 V. with no sign of a breakdown, both with and without liquid in the apparatus. The outer cylinder is rotated by means of a small motor and a worm reduction gear. Bronze bearings were used on the shaft and were the source of much trouble since the wear is rather excessive in this type of bearing, and any play in the shaft shows up immediately in an oscillation of the suspension when the apparatus is running. The motor and shaft are mounted on a base which can be readily moved so that the centering of the suspension is a simple matter. The whole apparatus is mounted on a steel plate which can be leveled by means of three leveling screws. The motor used to drive the apparatus was a 115 Volt, 1/20 H.P. D.C. shunt wound motor, rated to run at 1750 R.P.M. The reduction in the worm drive was 30/1, hence the normal speed of rotation of the cylinder was 58 R.P.M. Variation of speed was obtained by inserting resistances into the field and armature circuits. By increasing the

resistance in the armature circuit, the speed of the cylinder could be reduced to 10 R.P.M. before the motor became unstable. As the bearings of the shaft became worn, the lowest speed that could be reached was approximately 15 R.P.M. By increasing the resistance in the field circuit, the speed of the cylinder could be increased to 90 R.P.M. The speed of rotation of the cylinder was measured by counting the R.P.M. by eye for the low speeds and with a revolution counter for high speeds. It is very hard to control temperature in this type of apparatus so I made no provision for controling it. A check, however, on any variation in the temperature will be discussed in the technique of measurement.

Let us now consider the stability of such a system. Couette found that turbulence occurred in his apparatus using water at a Reynolds number of approximately 1900.

$$R = \frac{\Omega b(b-a)}{\nu}$$

where ν is the kinematic viscosity.

Couette's cylinders had a radius of 14.5 cm. and a gap of .2 cm. Mallock, using an apparatus with cylinders of 7 cm. radius and 2.5 cm. gap, found that turbulence occurred at Reynolds numbers ranging from 4200 to 32,000. Recently Taylor found that when he used cylinders of radius 4 cm., he could find no instability of flow at the highest speed of which his apparatus was capable.

R = 12,500 approximately. The highest speed used in my experiment was 90 R.P.M. Reynolds number then is

$$R = \frac{2\pi \times 90 \times 4.3 \times (4.3 - 3.8)}{.01 \times 60}$$

$$= 2000$$

Since this is well below the lowest critical value of Reynolds number found by either Mallock or Taylor, using instruments of comparable size, I conclude that the flow is laminar at all speeds at which my apparatus operates.

Since I had imposed the design condition that this amount of liquid used should be small, the dimensions of my viscosimeter were kept as small as was consistent with ease of construction and operation. The guard cylinders were made only twice as long as the gap, therefore the end effect was not completely eliminated. This is borne out by the two viscosity curves Fig. 5 and Fig. 6. For low speeds the graph of the R.P.M. vs. Deflection is curved and then becomes a straight line at higher speeds. Hatschek found similar results in his work. He found that this straight line continued until turbulence occurs, at which point a break appears. Hatschek investigated this curved position of the curve and showed that it was due to the end effect and could be eliminated by increasing the length of the guard cylinders relative to the gap. This effect renders

my apparatus unsuitable for the measurement of absolute viscosity, but in no way impairs its value for the measurement of relative viscosities insofar as only the straight portions of the curves are used. As a check on the accuracy of the instrument for the measurement of relative viscosities, I ran the viscosity curves for water and carbontetrachloride. The inverse of the slope of the straight portion of the curve gives a measure of the viscosity. Taking the viscosity of water as .0100, the computed value for carbontetrachloride is .0094 as compared with .0096 given in the Handbook for Physics and Chemistry. The accuracy of the instrument could be improved by using a more accurate method of observing the R.P.M.

Mechanically the stable position for the suspension is in the center as is also the case hydrodynamically. In the case of the electric field, however, the center position is unstable. This means that the electric field must be kept below the value at which electrical force is enough to overcome the hydrodynamical and mechanical forces and cause instability. By experiment this value of the field was found to be 3000 volts/cm. At fields lower than this critical value the field had no effect on the suspension when the outer cylinder was not in motion. Fields higher than 3000 volts/cm., however, caused the suspension to swing out until it was stopped by the guard cylinders. In

any future design this could be prevented by running the wire through the suspension and fastening it to the lower guard cylinder thus preventing any side motion of the suspension.

The source of voltage for this experiment was a 6000 volt, 20 K.W., D.C. generator. The output of the generator was put across a bank of 10 watt electric lamps. The different voltages for the instrument were obtained by tapping off at various places in the resistance bank. The control head for the generator had a voltmeter installed in it; however, this meter gave very inaccurate readings for the conditions under which I was working. I therefore placed a voltmeter across the instrument and read the voltages directly. This method also enabled me to check whether or not the liquid was conducting any current as actually happened in a few cases. Knowing the voltage across all the lamps and reading the voltage across the number of them in parallel with the instrument, the resistance of the instrument or the current passing through the instrument can easily be calculated. The passage of a current could also be noted visually by observing the brilliance of the lamps above and below the point where the instrument was connected. In one case the current drawn by the instrument was enough to burn out several of the lamps. The connection to the viscosimeter was fused with a .25 Amp. fuse wire to guard against any accident.

Let us now see how this design for the viscosimeter satisfies the conditions which we would like to have fulfilled in this experiment. Once equilibrium has been reached, the liquid does not tend to change in the gap so that the viscosity which I measure both with and without the field is of the same liquid. If there was any variation of temperature with time in the apparatus, the viscosity before and after the field had been on would differ. The results in general show that the viscosity before and after the field was on are identical, which indicates that the temperature change is negligible. The velocity gradient in the gap is given by equation 7). The velocity gradients, if computed at the inner and outer walls, however, differ by only 10%, so the second condition is fairly well satisfied. The gap across which the viscosity is measured is .5 cm., which is 50 times as large as that used in my previous arrangement. Once the liquid has reached equilibrium, the results of this thesis indicate that the increase of the viscosity does not depend upon the length of time that the field acts upon the liquid. The time required to make an observation on the viscosity is approximately three minutes. Therefore, there is no appreciable length of time between measurements and hence small chance for the properties of the liquid to change. The period of the suspension

is 10 seconds and the amount of damping depends upon the viscosity of the liquid used. In the case of air, it takes about two hours for a small oscillation to die out while with water it is of the order of one or two minutes. The amount of liquid required to fill the viscosimeter is 400 c.c., an amount which in general is easy to obtain.

TECHNIQUE OF MEASUREMENT

Before starting on any investigation other than that of checking the use of the viscosimeter for the measurement of relative viscosity, I consulted the table of dipole moments given by Fuchs and Wolf[3]. From this table, I tried to select a series of liquids which could be readily obtained in a fairly pure state and which would cover as far as possible the range of dipole moments commonly found in liquids. In any future investigations one should also select the liquids with regard to their viscosity, trying to keep the viscosities approximately the same, as one is then able to compare results readily. The liquids which I selected are given in Table III. I included a series of alcohols in this list as well as water, but upon trial I found that the conductivity of all of these liquids was too high to permit any observations being made on them. Water with a conductivity of 10^{-5} mhos burned out the fuse in the line. The chemicals for this research were obtained from the Chemistry Department at this school, and in general there is no accurate information as to the purity of the specimens. The chloroform, ether, benzene and acetone were commercially C.P. samples. The remainder of the specimens, however, were obtained from the general stock, with the exception of the nitro-

benzene supply which was prepared for me by Mr. A. N. Prater and had a boiling point of 208.4° C. The method of observing the deflections of the suspension was to read a scale reflected by the mirror in a small telescope. The scale used was a straight one, 1 meter in length. The distance of the scale from the mirror was 1.6 m.. The objective of the telescope was directly under the scale and at the same distance from the mirror. The deflections, therefore, will not be directly proportional to the scale reading. The corrections to the scale readings are given in the form of a graph in Fig. 4a. All of the deflection readings given in this thesis have been corrected for this error. The method of measurement is as follows: The liquid is poured into the instrument and allowed to stand for about one hour in order to enable it to reach an equilibrium with the surroundings. In the early part of the experimental work, I found that some of the liquids showed an extremely high effect when first poured in. This effect decreased with time until finally a constant value was reached. I attribute this decrease with time to the fact that the liquid was not in equilibrium with the surroundings. An example of this is given in Table V where the change of the effect with time is recorded. In this case temperature equilibrium had been established but the air was still disolving into the liquid. In general, this was the case with most of the volatile liquids.

This could be avoided if the liquid was set out in an open dish for an hour or two before starting the experiment. After this equilibrium has been reached a reading is made to determine the zero deflection. This zero deflection has been subtracted from all the readings listed in the tables. This zero reading must be subtracted from the deflection before it has been corrected for the nonlinearity of the scale, for it essentially locates the foot of the perpendicular from the scale to the mirror. The maximum field to be used is then turned on and the stability of the suspension is observed. If this is unstable the maximum field at which the suspension is still stable must be determined and this field must not be exceeded during the test. In all the liquids I tested the suspension was stable for at least 2000 volts/cm. field. The motor is then started and the resistances adjusted until the desired deflection of the suspension is obtained. This deflection when corrected for zero deflection and nonlinearity of scale I have recorded in the tables as D_1. The field is then put across the instrument and the voltage recorded. When the oscillations of the instrument have been damped out the deflection is read. In general, one is not able to read this to better than .5 cm. since the oscillations never quite die out. This deflection when corrected I have recorded in the tables as D_2. The field is then turned off and the deflection when corrected is

recorded as D_3. In general, D_1 and D_3 should be the same. If the temperature rises while the field is on, the D_3 reading will be lower than D_1 since the viscosity of the liquid is lowered. In Table VIII we see that when the field was left on for $\frac{1}{2}$ hour, the D_3 reading is approximately the same as D_1, the slight increase being due to a variation in motor speed. The voltage source for the D.C. driving motor was the 130 Volt generator, which was in general use by the whole department, hence the voltage would vary from time to time and my motor speed would not remain constant to more than 1 or 2 R.P.M. over any great period of time. Since the time between readings is usually very small, the error introduced by this variation of motor speed is negligible. When the test is finished the liquid is drained out by means of a drain plug in the bottom of the outer cylinder and the instrument carefully washed out with carbontetrachloride. This makes a very good washing agent since the effect of an electric field on it is zero. In some cases I checked the amount of contamination from the previous liquid by making a check run on carbontetrachloride. With nitrobenzene, I did not remove the liner when I cleaned the apparatus, and when I checked carbontetrachloride I observed a small effect on the viscosity when I put on the electric field. This then is a rather delicate test on the amount of contamination in the liquid. Table VIII gives some data on some C.P. Braun

acetone and it is noted that the data are very inconsistent. I attribute this to impurities in the acetone for when I ran a test on C.P. Merck acetone I obtained the results recorded in Table XI which show much better consistency. In one or two cases the liquid conducted enough current to lay down a small deposit on the suspension. It would be exceedingly difficult to clean the suspension itself so the method I used was to reverse the direction of the field from the generator and cause the deposit to be removed from the suspension and to be deposited on the liner which is easily removed and cleaned. This reverse of field should be done in the generator control room since this leaves the same side of the instrument grounded. If I were to reverse the field by just changing the connections to the viscosimeter this would put the D.C. driving motor at a high potential, but this is grounded through its electrical circuit, hence we would have a dead short across the big generator. Table V shows the value of the effect when the generator field is reversed. The voltage reading in this case was made on the generator control head voltmeter which is not very accurate.

The accuracy of the percentage changes, I estimate to be about 10%. The accuracy of course varies greatly with the magnitude of the change, the higher the change the more accurate

the result. This is because we are taking the difference of two readings whose accuracy remains constant. However, when the change is small the suspension does not oscillate very much and the accuracy of the reading D_2 is greatly improved, also the time between readings is reduced which helps to eliminate any error due to variation in speed of the motor.

TABLE III

Table of Liquids Investigated

	Liquid	Viscosity	Dipole Moment - 10^{18}
1.	Chloroform	.0056	1.15
2.	Ether	.0023	1.14
3.	Carbontetrachloride	.0096	0
4.	Nitrobenzene		3.95
5.	Acetone	.0033	2.73
6.	Benzene	.0065	0
7.	Ethel Acetate	.0044	1.81
8.	Toluene	.0058	.4
9.	Xylene-meta	.0061	.4
10.	Decalin		0
11.	n-butyl bromide	.0294	1.9
12.	Aniline	.044	1.53

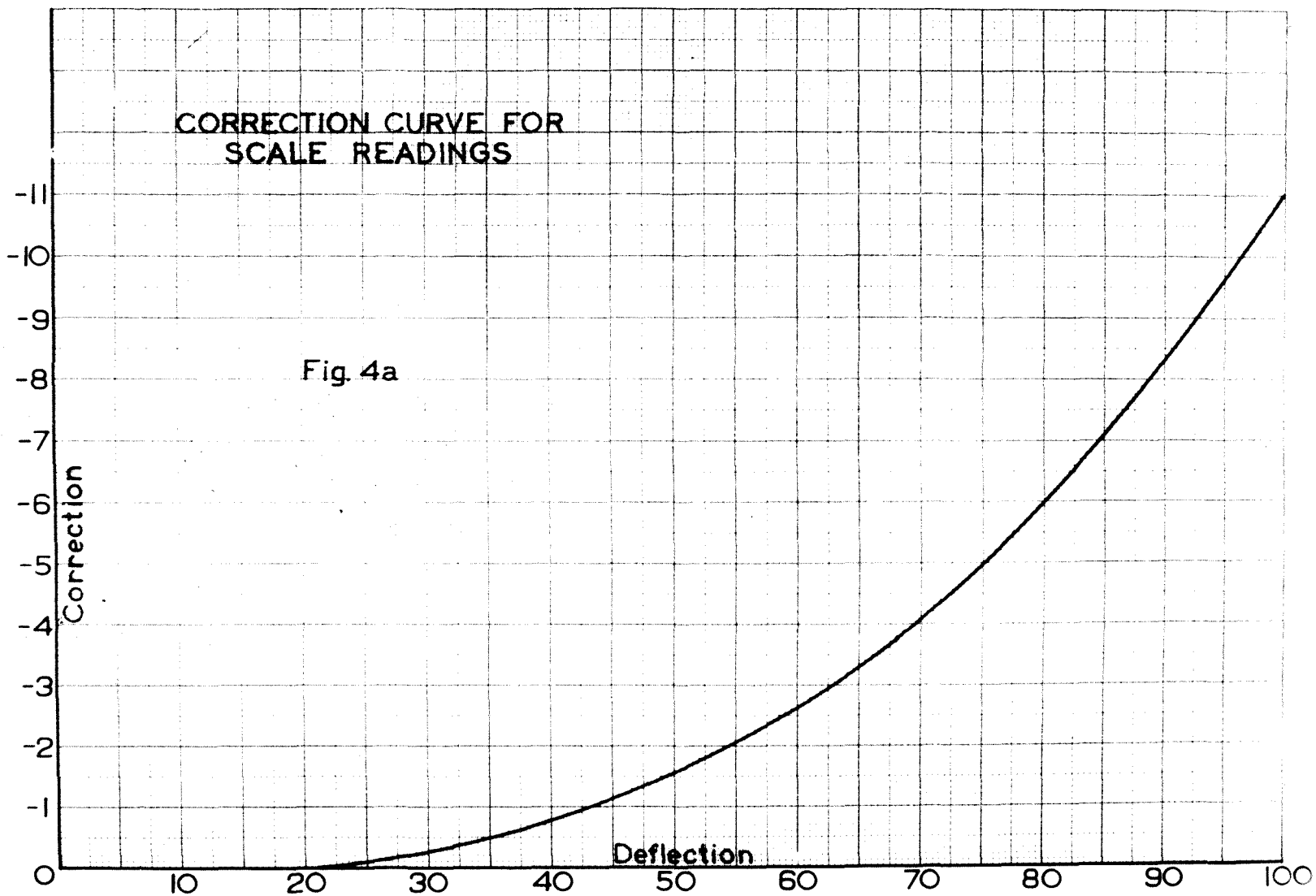


TABLE IV

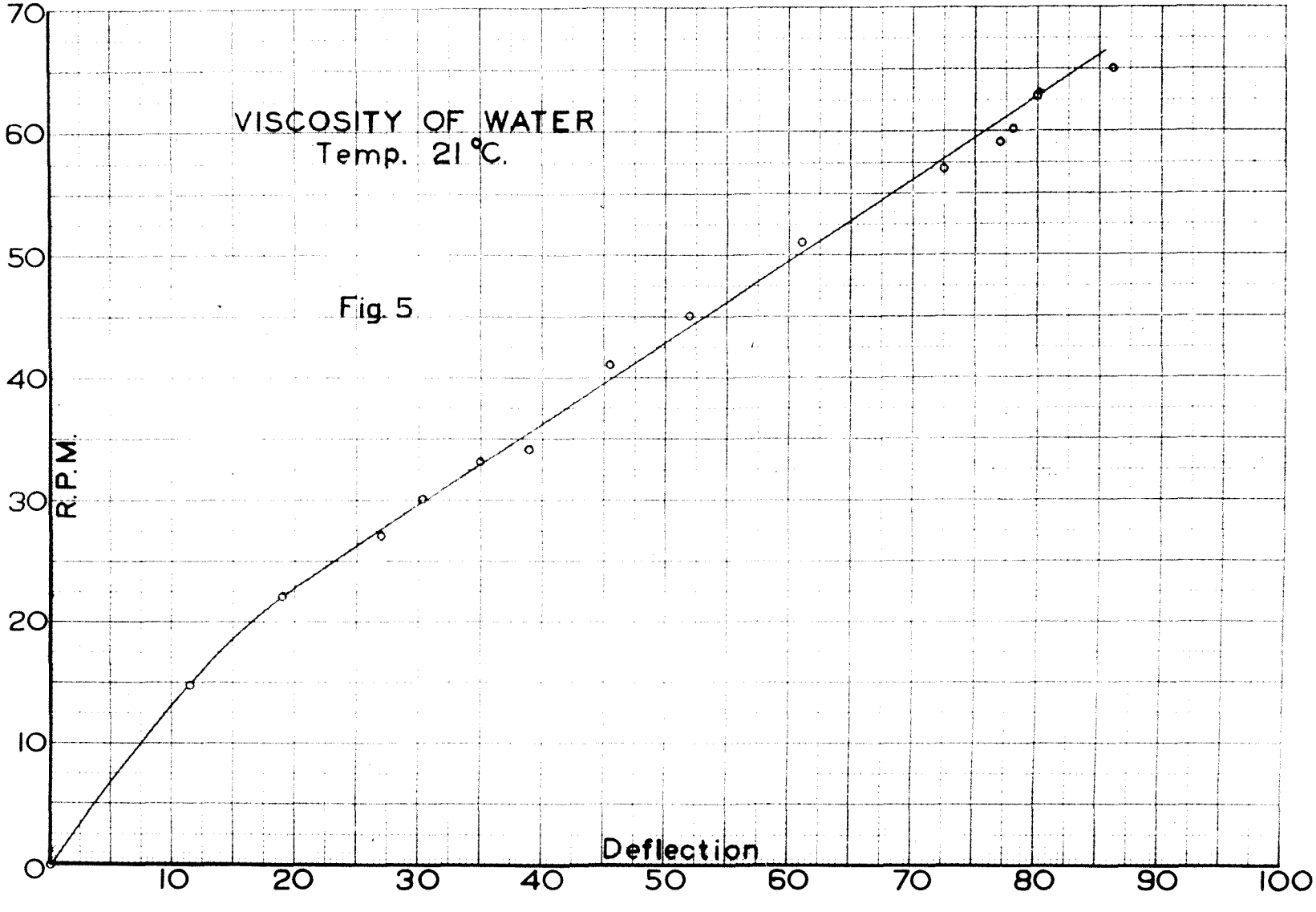
Viscosity Data

Water — Temp. 20°C — 3/13/35

RPM	Defl.	RPM	Defl.
0	0	34	39
60	78	33	35
65	86	30	30.5
59	77	27	27
57	72.5	22	19
51	61	14.5	11.5
45	52	63	80
41	45.5	0	0

Carbon Tetrachloride — Temp. 21°C

RPM	Defl.	RPM	Defl.
0	0	31	17
39	50	61	81
30	35.5	50	60
25	28	39	48
		28	34
		0	0


VISCOSITY OF WATER
Temp. 21 °C.
Fig. 5
R.P.M.
Deflection
0
10
20
30
40
50
60
70
10
20
30
40
50
60
70
80
90
100

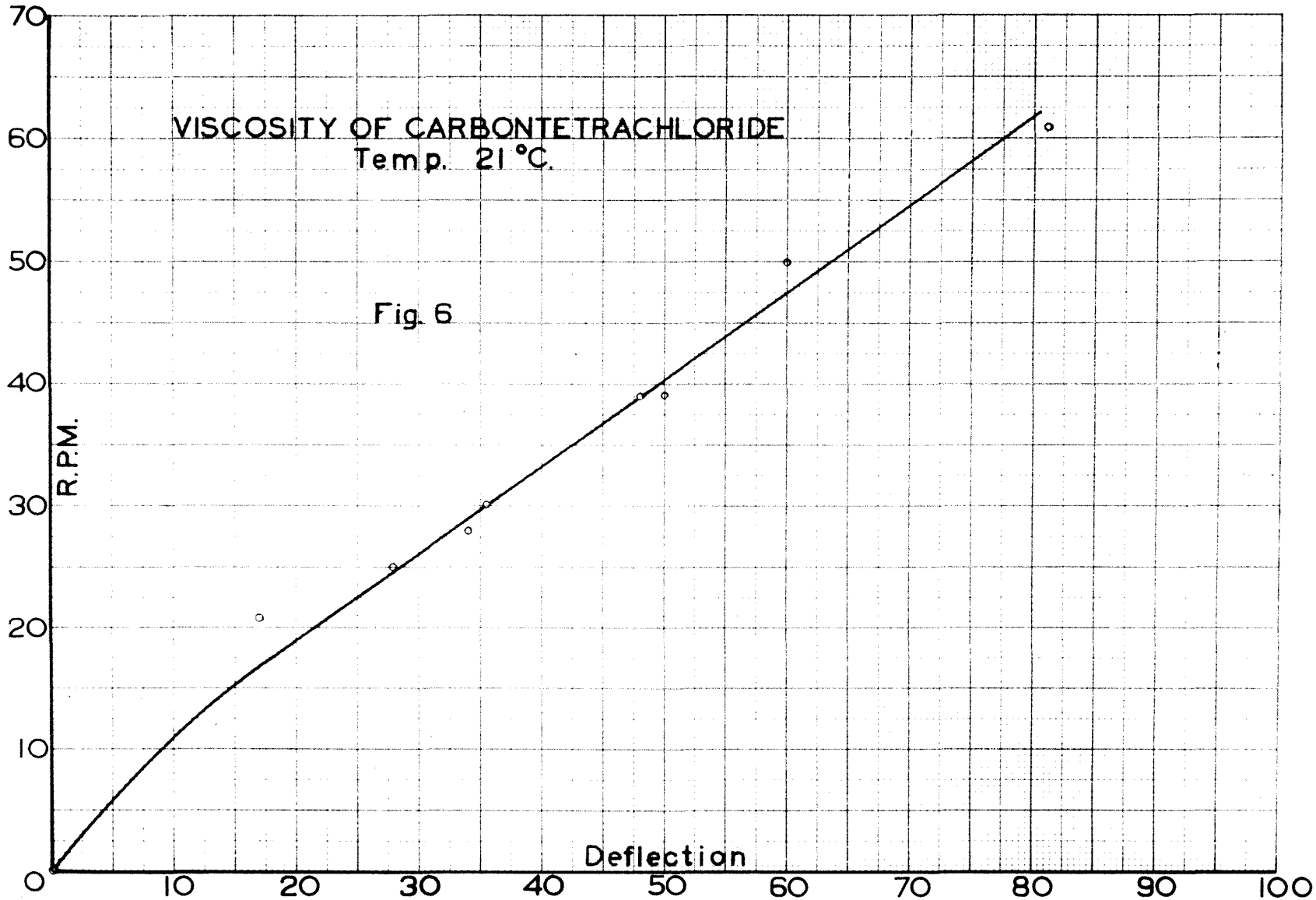

VISCOSITY OF CARBONTETRACHLORIDE
Temp. 21 °C.
Fig. 6
R.P.M.
Deflection
0
10
20
30
40
50
60
70
80
90
100

TABLE V

Data

Chloroform C.P. Temp. 23° 3/26/35

Zero Defl. 5.5 cm.

RPM	D_1	D_2	D_3	V/cm.	% Change
42	37	80	38	1760	110
	38	73.5	38	1580	93
44	38.5	64	39.5	1410	64
	39.5	56	39.5	1230	42
	40	49	40.5	1060	21
	41.5	45.5	41.5	880	10
	42.5	41.5	42.5	700	- 2
	42.5	40.5	42	530	- 3
	42	42.5	42.5	350	0
	42.5	40.5	42.5	530	- 3
	43	41.5	43	700	- 2
49	43.5	47	43.5	880	10
	43.5	51	43.5	1060	17
	43.5	54.5	43.5	1230	25
	43.5	60.5	44	1410	38
	44	65	43.5	1580	50
	43.5	71.5	43.5	1760	65
0	6	6	6	1760	0
0	6	6	6	1760	0

TABLE V (cont'd)

Data

Chloroform C.P. Temp. 21° 3/29/35

Zero Defl. 3.5 cm.

Time	D_1	D_2	D_3	V/cm.	% Change
1:15	20	48	20	1760	144
1:25	20	44.5	20	1580	122
1:30	20.5	40	20.5	1410	95
1:35	21	37	21	1230	76
1:40	21	33	21.5	1060	55
1:45	21.5	29	21	880	33
1:50	21	24	21	700	14
2:00	21	21	21	530	0
2:05	21	47		1760	134
2:15		46		1760	130
2:30		46	21	1760	130

TABLE V (cont'd)

R.P.M. 28

RPM	D_1	D_2	D_3	V/cm.	% Change
40	37	65.5	37	1760	77
63	65.5	71.5	65.5	880	9
		unstable			
	28	60.5	32	1760	102
*	32.5	65	33	1760	97
	33.5	65	36	1760	90
	36	67	37	1760	84
	28	56.5	30	1760	100
	30	66	37	1760	94
	37	67.5	38	1760	84
	38	65	38	-1760	72

*Took chloroform out of apparatus and poured it back in again.

TABLE V (cont'd)

Data

Chloroform C.P. Temp. 23° 3/28/35

Zero Defl. 3.5 cm.

Time	D_1	D_2	D_3	V/cm.	% Change
4:05	20.5	48	22.5	1760	124
4:08	21	46	22	1760	119
4:15	31	58.5	31.5	1760	89
4:23	31.5	58.5	31.5	1760	86
4:48	31	58.5		1760	89
4:53		55.5		1760	79
4:58		54.0		1760	74
5:03		55	31	1760	78
5:07	31	55.5	31	1760	79
5:12	30	51.5	31	1580	66
5:18	31.5	47	32	1410	49
5:23	32	42.5	32	1230	33
5:28	32	39	32	1060	22
5:33	32	36	32	880	12
5:38	32	33	32	700	3
5:43	33	58.5	34	1760	77

TABLE VI

Data

Ether (diethyl) C.P. Temp. 21° 3/29/35

Zero Defl. 6 cm.

D_1	D_2	D_3	V/cm.	% Change
19	52	20	1760	160
20	45.5	20.5	1410	123
20.5	34.5	20.5	1060	68
20.5	24	20.5	700	17
20.5	53	20.5	1760	159
21	48.5	21	1580	137
20.5	39	20.5	1230	90
20	27.5	20	880	37
19.7	20.5	19.7	530	4
20	49.5	20	1760	147
20	32	20	1060	60
20	48.5	20	1760	143
20	40	20	1410	100
20	49.5	20	1760	147
20	23	20	700	15
20	48.5	20	1760	143
11	31.5	11	1760	186
11	32	11	1760	190
11.5	31	11.5	1580	170
11.5	34.5	11.5	1760	209

TABLE VI (cont'd)

Data

Ether (diethyl) C.P. Temp. 21° 3/29/35

Zero Defl. 6 cm.

D_1	D_2	D_3	V/cm.	% Change
11.5	34.5	11.5	1760	200
11	30.5	11	1580	176
11	27	11	1410	145
11	24	11	1230	118
11	33.5	11	1760	204
11.5	24*	11.5	1230	108
13	23	13	1060	77
13	26.5	13	1230	104
13	29.5	13	1410	27
13	32.5	13	1580	150
13	36	13	1760	178
13	23	13	1060	77
13	20	13	880	54
13	16.5	13	700	27
13	14	13	530	7
13	36	13	1760	177
13	26.5	13	1230	104
20	48.5	20	1760	143

* Generator stopped for 5 minutes.

TABLE VII

Data

Nitrobenzene B.P. Temp. 20°C 3/30/35

Zero Defl. 6 cm.

	RPM	D_1	D_2	D_3	V/cm.	% Change
	18	26.5	41	26.5	880	55
*		26.5	42	27	880	58
	37	68.5	68.5	68.5	170	0
		69.5	72.5	69.5	350	4
		69.5	71.5	69.5	350	3
		69.5	80	69.5	530	15
	26	45	59	45	530	31
		45	49.5	46	350	8
		45	49.5	46	350	8
		47	79	49	880	64
		45	79	47	880	71
		45	67.5	45	700	50
		45	57	45	530	27
		45	47.5	45.5	350	5
		45.5	49	45.5	350	8

* Motor unstable at this speed.

TABLE VII (cont'd)

Data

Nitrobenzene B.P. Temp. 20°C 3/30/35

Zero Defl. 6 cm.

RPM	D_1	D_2	D_3	V/cm.	% Change
23	38	41	38	350	8
	38.5	42	38.5	350	9
	38.5	65	38.5	880	70
	37.5	69	39.5	880	70
	39	58	39	700	49
	37.5	51	39.5	530	29
	39	51	39	530	30
	38	65	40	880	66
	39	73	41	1060	82
	39	unstable	39	1230	--
	39	59	39	700	51
26	45	66.5	44	700	49
37	68.5	79	68.5	530	15

TABLE VIII

Data

Acetone C.P. Braun Temp. 21°C 3/30/35

Zero Defl. 6 cm. 38 R.P.M.

D_1	D_2	D_3	V/cm.	% Change
18	26	18	530	44
18	20	18	350	11
18	31.5	18	700	75
18	41	18	880	128
18	24	18	530	33
18	35	18	1060	94
18	22.5	18	530	25
18	25	18	700	39
18	28.5	18	880	58
* 18	69	18	1760	280
18	off scale	18	1760	--
18	27	18	350	50
18	33.5	18	530	85
18	42.5	18	700	136
18	47.5	18	880	164
18	38.5	18	700	108
18	19	18	170	5
18	21	18	350	17

* Data taken on 3/31/35

TABLE VIII (cont'd)

Data

Acetone C.P. Braun Temp. 21°C 3/30/35

Zero Defl. 6 cm. 38 R.P.M.

D_1	D_2	D_3	V/cm.	% Change
18	27	18	530	50
18	24	18	530	33
18	32.5	18	700	80
18	39		880	116
		Generator left		
	32.5	on for 1/2 hr.	880	80
	32	"	880	78
	39.5		880	19
	38		880	110
	43	19	880	138
18	18	18	170	0
18	19.5	18	350	8
18	25.5	18	530	41
18	33	18	700	83
18	42	18	880	133
				3/31/35
18	52	18	1060	190
18	64	18	1230	255
18	36.5	18	530	103
18	34.5	18	530	91

No evidence of current flow through apparatus.

TABLE IX

Data

Xylene - meta Temp. 20°C 4/2/35

Zero Defl. 5 cm.

	D_1	D_2	D_3	V/cm.	% Change
	33	38	33	1760	15
	34.5	39.5	34.5	1760	14
	26	32.5	26	1760	25
	24	31.5	24	1760	31
	16	29	16	1760	82
	25	31.5	25	1760	26
	25	24	25	1580	16
	25	28	24.5	1410	12
	25	28	25	1410	12
	25	26.5	25	1230	6
	15.5	29.5	15.5	1760	90
	15	26	15	1580	73
	15.5	21.5	15	1410	41
	15	18	15	1230	20
	15	16	15	1060	7
	20.5	22	20.5	1060	7
	20.5	23	20.5	1230	12
	20.5	24.3	20.5	1410	18
	20.5	26.5	20.5	1530	29
	20.5	30	20.5	1760	47
	20.5	26.5	20.5	1530	29
*	25	31.5	25	1760	26
	25	31	25	1760	24
	20	29	20	1760	45
	15	30	15	1760	100

* Check run made on 4/3/35.

TABLE X

Data

Toluene Temp. 21°C 4/3/35

Zero Defl. 5 cm.

D_1	D_2	D_3	V/cm.	% Change
25.5	28	25.5	1760	10
26	29	26	1760	12
26	28	26	1580	8
26	27	26	1410	4
16	19	16	1410	19
16	17.5	16	1230	9
16	20	16	1580	25
16	21	16	1760	31
25.5	28.5	25.5	1760	12
26	29	26	1760	12
27	29	27	1580	8
26.5	28.5	26.5	1580	8
16	21.5	18	1580	26
16.5	21	17.5	1580	23
17	19	17	1230	12
16.5	18.5	16.5	1230	12
16	17	16	1060	6

TABLE XI

Data

Acetone C.P. Merck Temp. 20°C 4/3/35

Zero Defl. 5 cm.

D_1	D_2	D_3	V/cm.	% Change
25.5	62	25.5	720	142
25.5	59	25.5	710	130
25.5	58	25.5	720	128
25.5	57.5	25.5	725	128
25.5	49.5	25.5	600	94
25.5	50.5	25.5	600	98
25.5	40.5	25.5	460	59
25.5	41	25.5	460	61
25.5	31	25.5	310	22
25.5	31	25.5	320	22
30	36.5	30	320	22
30	47.5	30	470	58
30	58.5	30	600	95
30	66.5	30	800	122
30	67	30	800	124
30	58.5	30	640	95
30	49.5	30	480	64
30	37.5	30	320	25

Current through apparatus .015 amperes

Resistance of Acetone in apparatus 20,000 ohms.

TABLE XII

Data

Decahydronaphthalene (Decalin) Temp. 21°C 4/3/35

Zero Defl. 5 cm.

D_1	D_2	D_3	V/cm.	% Charge
83	87	83	1760	5
53	59	53	1760	11
52.5	58.5	52.5	1760	11
52.5	58.5	53.5	1410	10
55	60	55.5	1410	9
55.5	58.5	56	1060	5
56	58.5	56	880	5
56.6	58.5	56.5	700	4
57	58	57	530	2
57	57	57	350	0
57.5	63.5	57.5	1760	11

TABLE XIII

Data

Ethyl Acetate Temp. 21°C 4/3/35

Zero Defl. 5 cm.

D_1	D_2	D_3	V/cm.	% Change
25.5	52	24	1760	116

Resistance of Ethyl Acetate 2800 ohms.

Current through apparatus .086 amperes.

Temperature change was too much to make further measurements.

TABLE XIV

Data

Aniline Dipole moment 1.53 4/6/35

Temp. 21°C Zero Defl. 6 cm.

D_1	D_2	D_3	V/cm.	% Change
72.5	72.5	72.5	176	0
74.5	74.5	74.5	440	0
74.5	74.5	74.5	880	0
74.5	79	74	1600	7

TABLE XV

Data

n-butyl bromide B.P. 101-104 Dipole moment 1.9 4/5/35

Temp. 22° C Zero Defl. 5.5 cm.

D_1	D_2	D_3	V/cm.	% Change
28	35	30	880	21
30	28	30	700	- 7
30	28	30	700	- 7
30	33	30	880	10
30	33.5	30	880	12
30.5	41.5	30.5	1060	36
30.5	42.5	30.5	1060	39
30.5	28.5	30.5	700	7
30.5	50	30.5	1230	64
30.5	41.5	30	1060	38
30	59.5	30	1410	98
30.5	64.5	30	1580	115
30.5	57	29.5	1410	90
30.5	41.5	30	1060	38
29.5	63	29.5	1580	114
29.5	67.5	28.5	1760	132
46	65.5	47	1230	39
47	65.5	47	1230	39
47	75	46.5	1410	62
47	84	47	1580	79
47	54.5	46	1060	17
49	49	49	880	0

TABLE XVI

Data

Carbontetrachloride C.P. Temp. 21°C 3/28/35

Zero Defl. 3.5 cm.

D_1	D_2	D_3	V/cm.
20	20	20	1760
20	20	20	880
15	15	15	1760
15	15	15	880
40	40	40	1760
40	40	40	880
60	60.5	60	1760
60	60	60	1760
60	60	60	880
80	80	80	880
80	80	80	1760

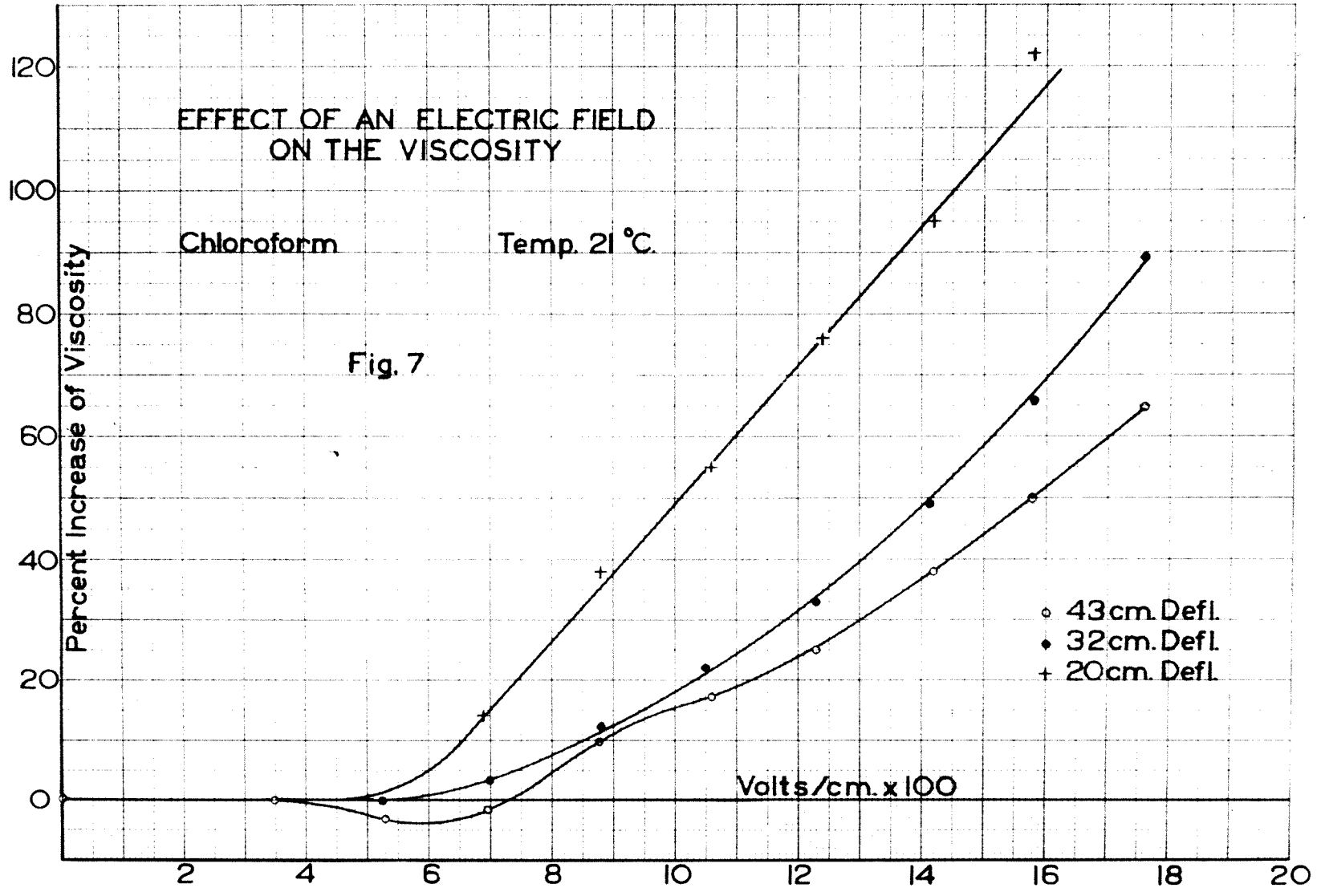
TABLE XVII

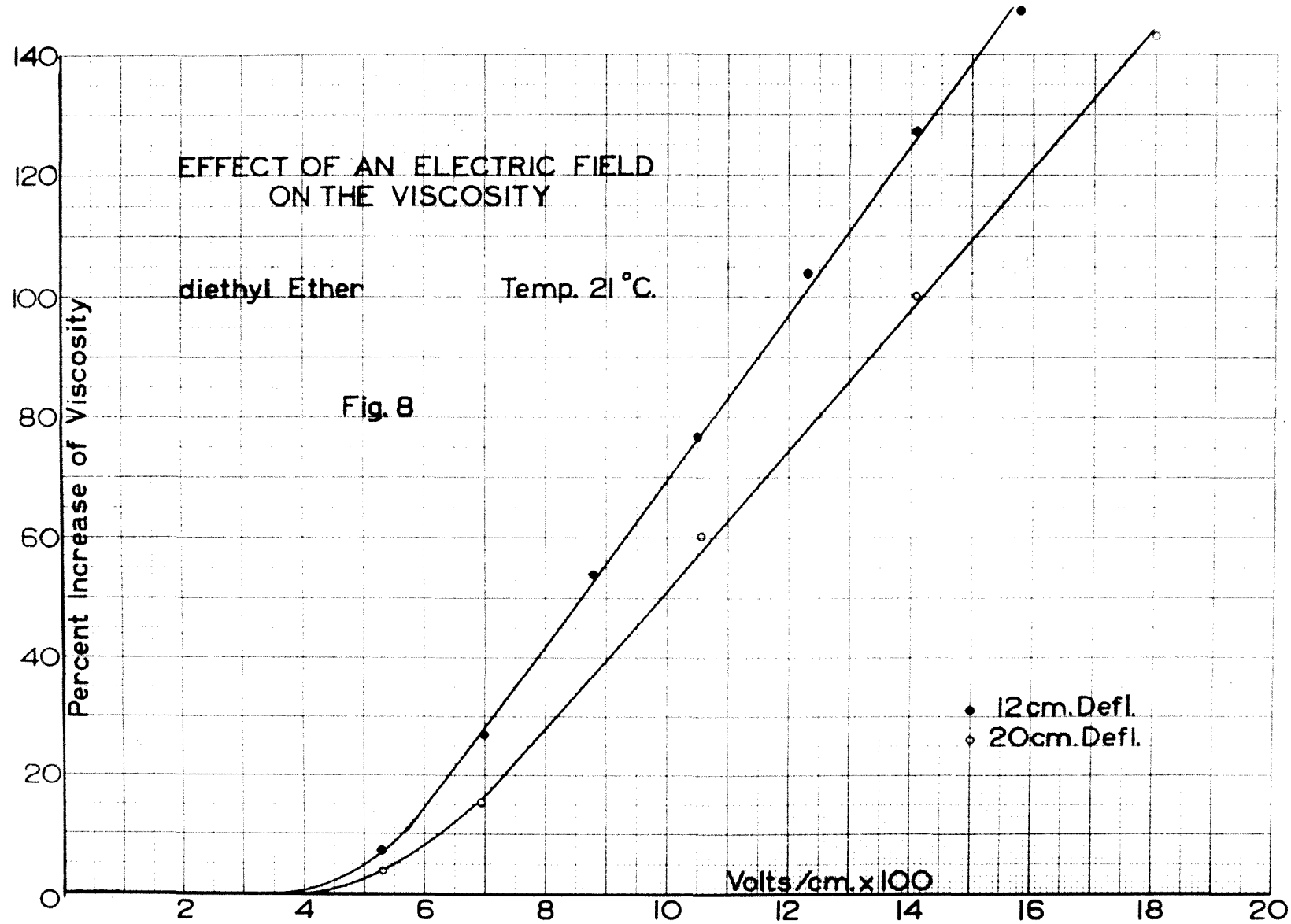
Data

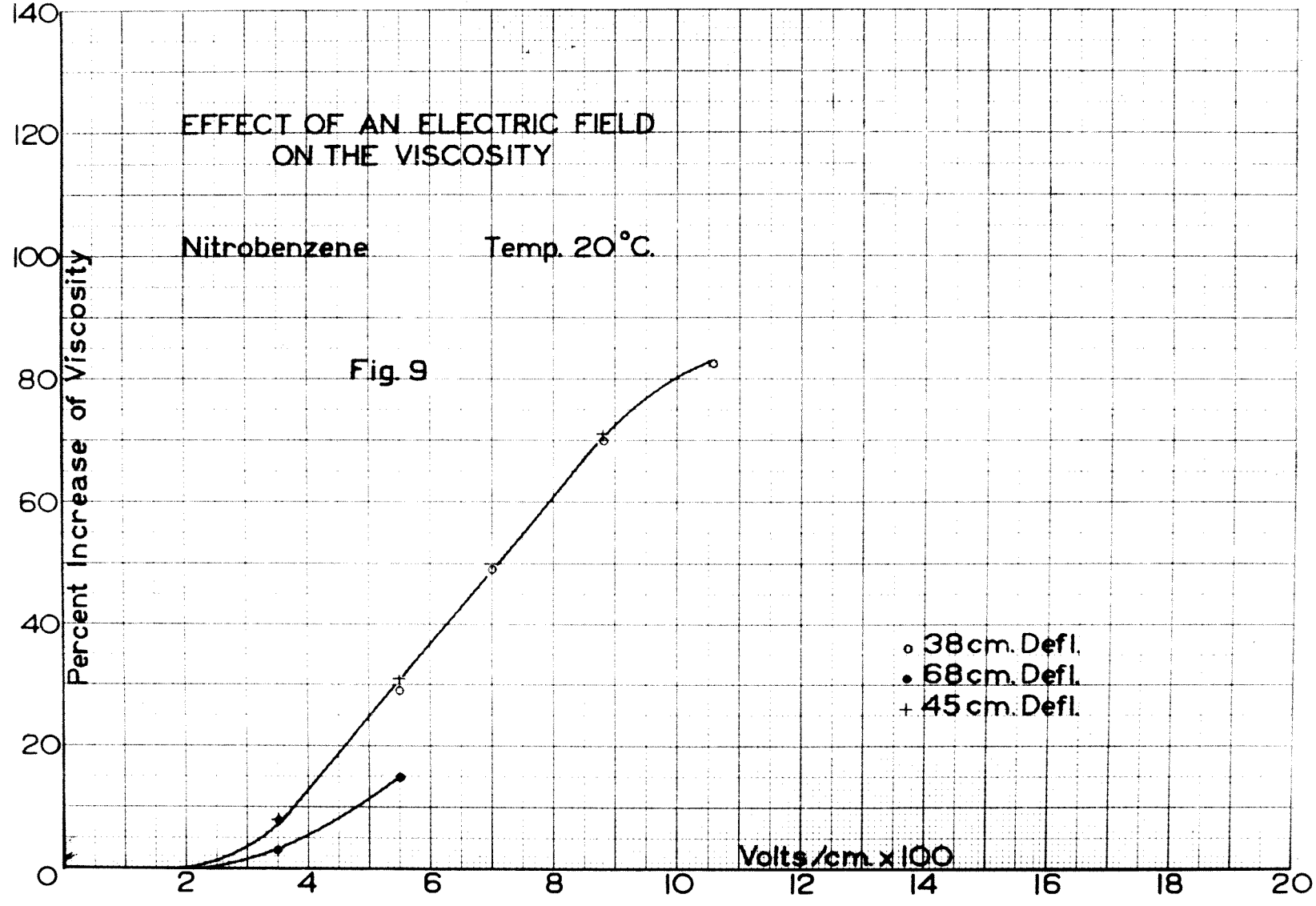
Benzene C.P. Temp. 21°C 3/30/35

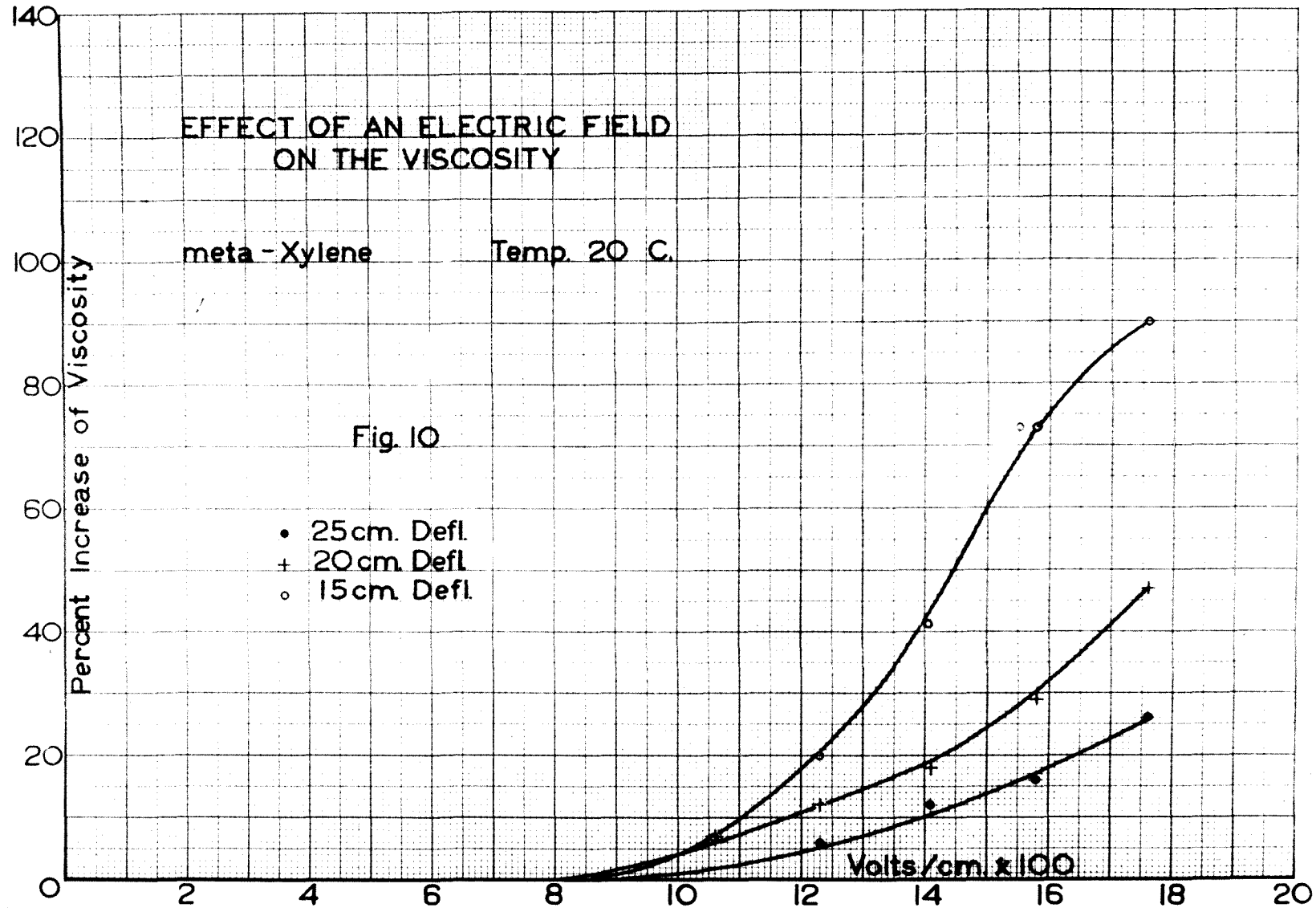
Zero Defl. 6 cm.

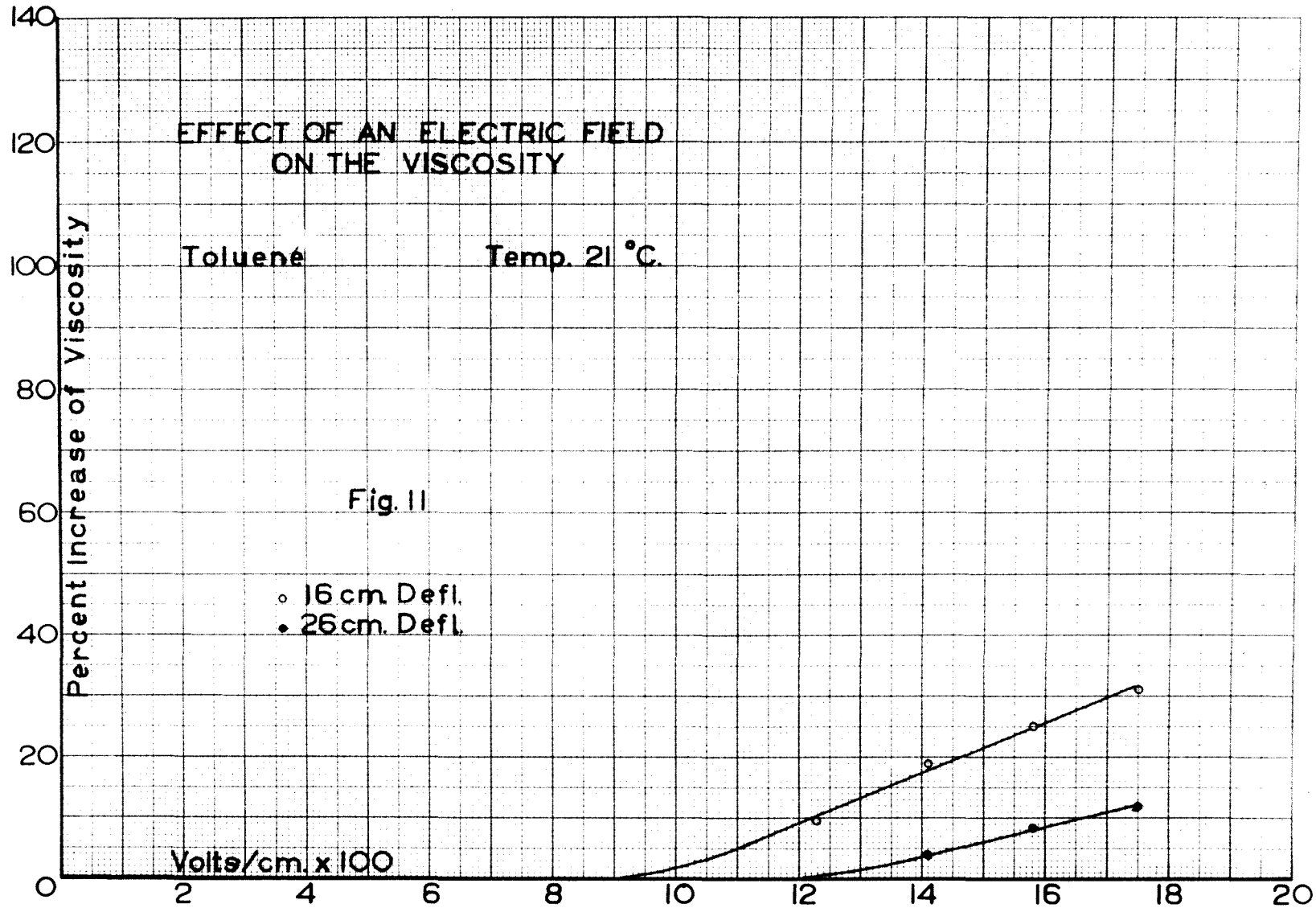
D_1	D_2	D_3	V/cm.
20	20	20	1760
20	19.5	20	880
20	20	19.5	1760
40	40.5	40	1760
40	40	39.5	1760
40	40	40	880
60	60.5	60	1760
60	59.5	59.5	1760
60	60	60	880

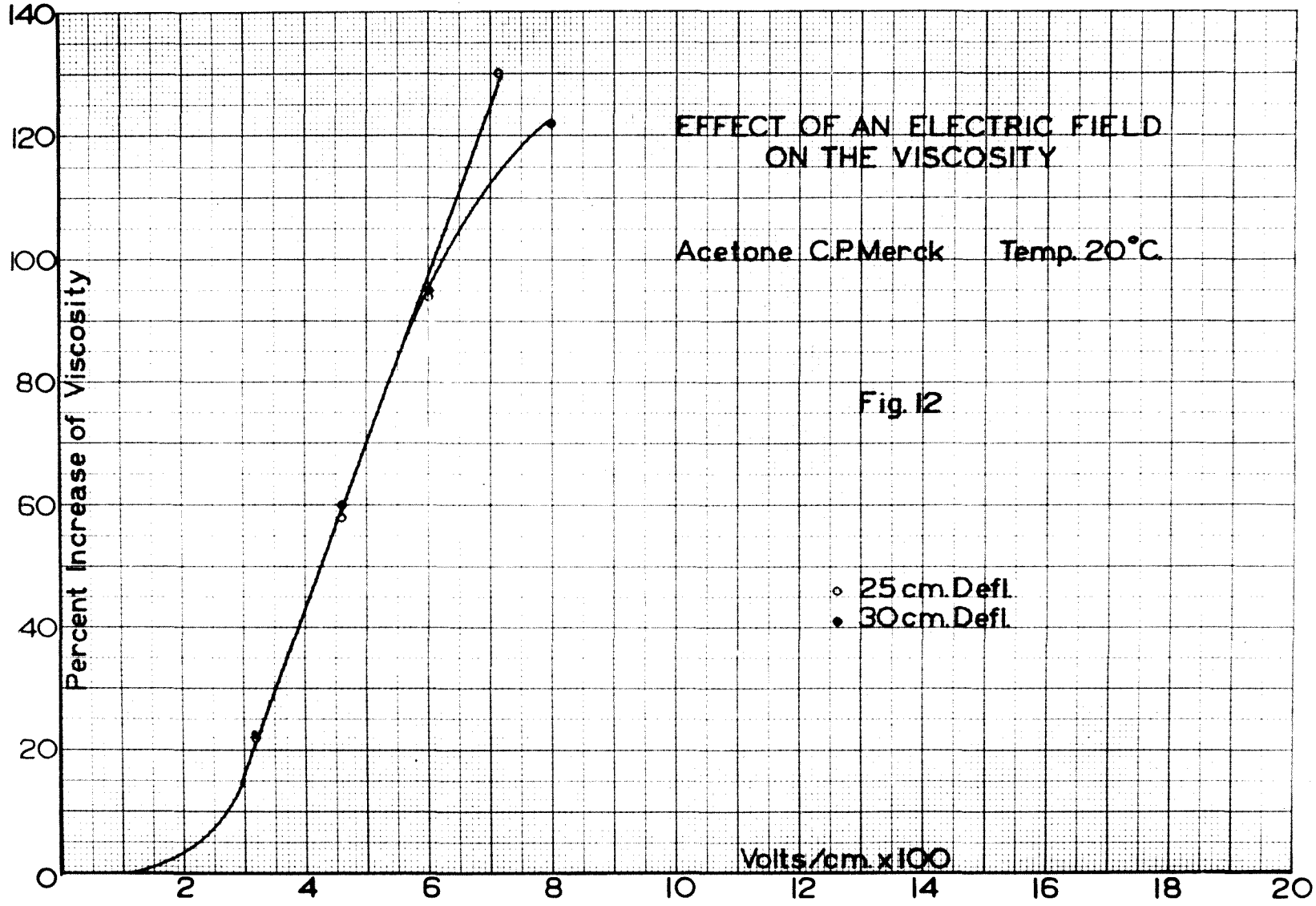

EFFECT OF AN ELECTRIC FIELD
ON THE VISCOSITY
Chloroform
Temp. 21 °C.
Fig. 7
Percent Increase of Viscosity
Volts/cm. x 100
43cm. Defl.
32cm. Defl.
20cm. Defl.
0
20
40
60
80
100
120
2
4
6
8
10
12
14
16
18
20

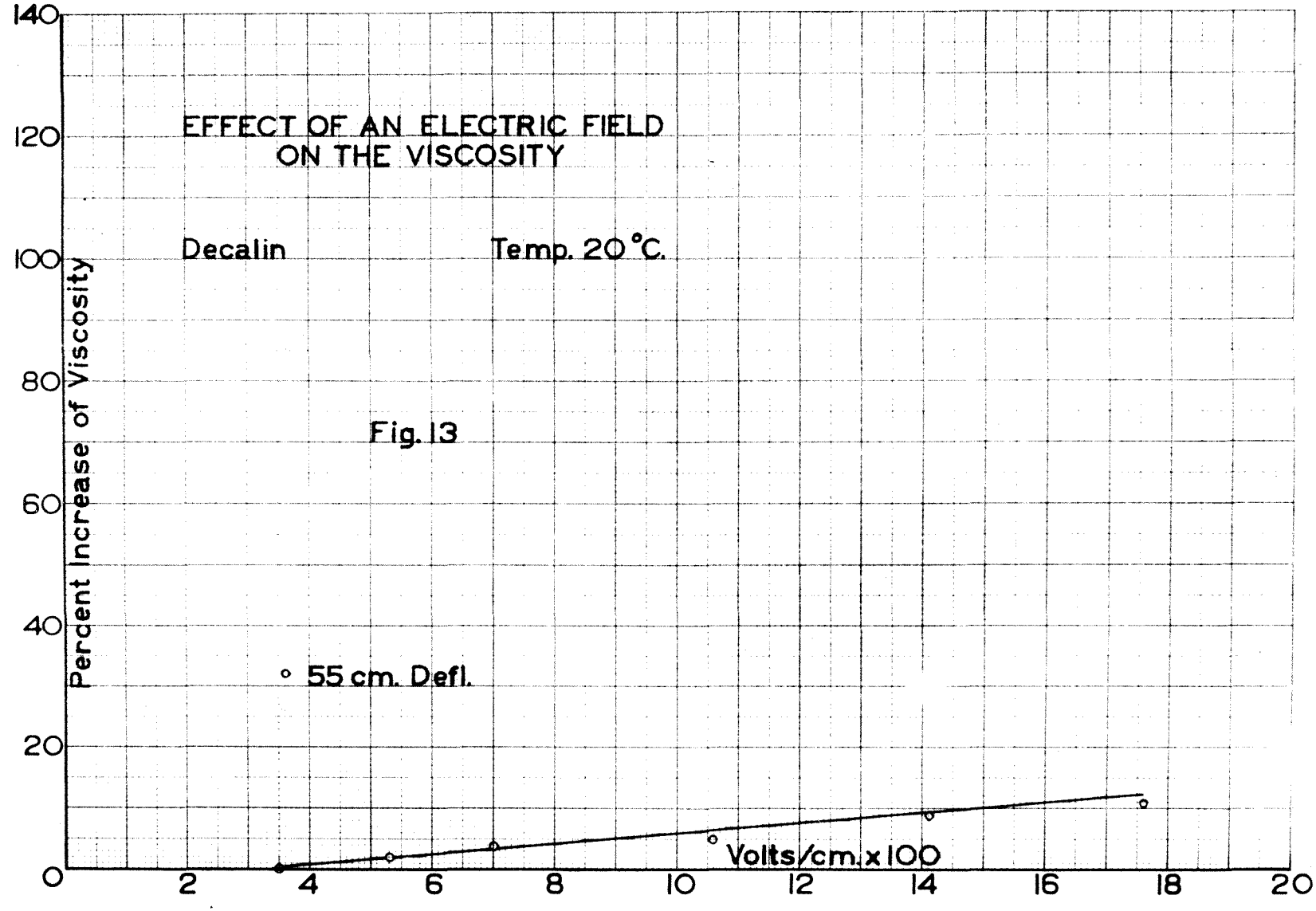

EFFECT OF AN ELECTRIC FIELD
ON THE VISCOSITY
diethyl Ether
Temp. 21 °C.
Fig. 8
Percent Increase of Viscosity
Volts/cm. x 100
12 cm. Defl.
20 cm. Defl.
0
20
40
60
80
100
120
140
2
4
6
8
10
12
14
16
18
20


EFFECT OF AN ELECTRIC FIELD
ON THE VISCOSITY
Nitrobenzene
Temp. 20°C.
Fig. 9
Percent Increase of Viscosity
Volts/cm. x 100
o 38 cm. Defl.
• 68 cm. Defl.
+ 45 cm. Defl.
0
20
40
60
80
100
120
140
2
4
6
8
10
12
14
16
18
20


EFFECT OF AN ELECTRIC FIELD
ON THE VISCOSITY
meta - Xylene
Temp. 20 C.
Fig. 10
• 25 cm. Defl.
+ 20 cm. Defl.
∘ 15 cm. Defl.
Percent Increase of Viscosity
Volts/cm. x 100
0
20
40
60
80
100
120
140
2
4
6
8
10
12
14
16
18
20


EFFECT OF AN ELECTRIC FIELD
ON THE VISCOSITY
Toluene
Temp. 21 °C.
Fig. 11
○ 16 cm. Defl.
• 26 cm. Defl.
Percent Increase of Viscosity
Volts/cm. x 100
0
20
40
60
80
100
120
140
2
4
6
8
10
12
14
16
18
20


EFFECT OF AN ELECTRIC FIELD
ON THE VISCOSITY
Acetone C.P. Merck Temp. 20°C.
Fig. 12
25 cm. Defl.
30 cm. Defl.
Percent Increase of Viscosity
Volts/cm. x 100
0
20
40
60
80
100
120
140
2
4
6
8
10
12
14
16
18
20


EFFECT OF AN ELECTRIC FIELD
ON THE VISCOSITY
Decalin
Temp. 20 °C.
Fig. 13
Percent Increase of Viscosity
55 cm. Defl.
Volts/cm. x 100
0
20
40
60
80
100
120
140
2
4
6
8
10
12
14
16
18
20

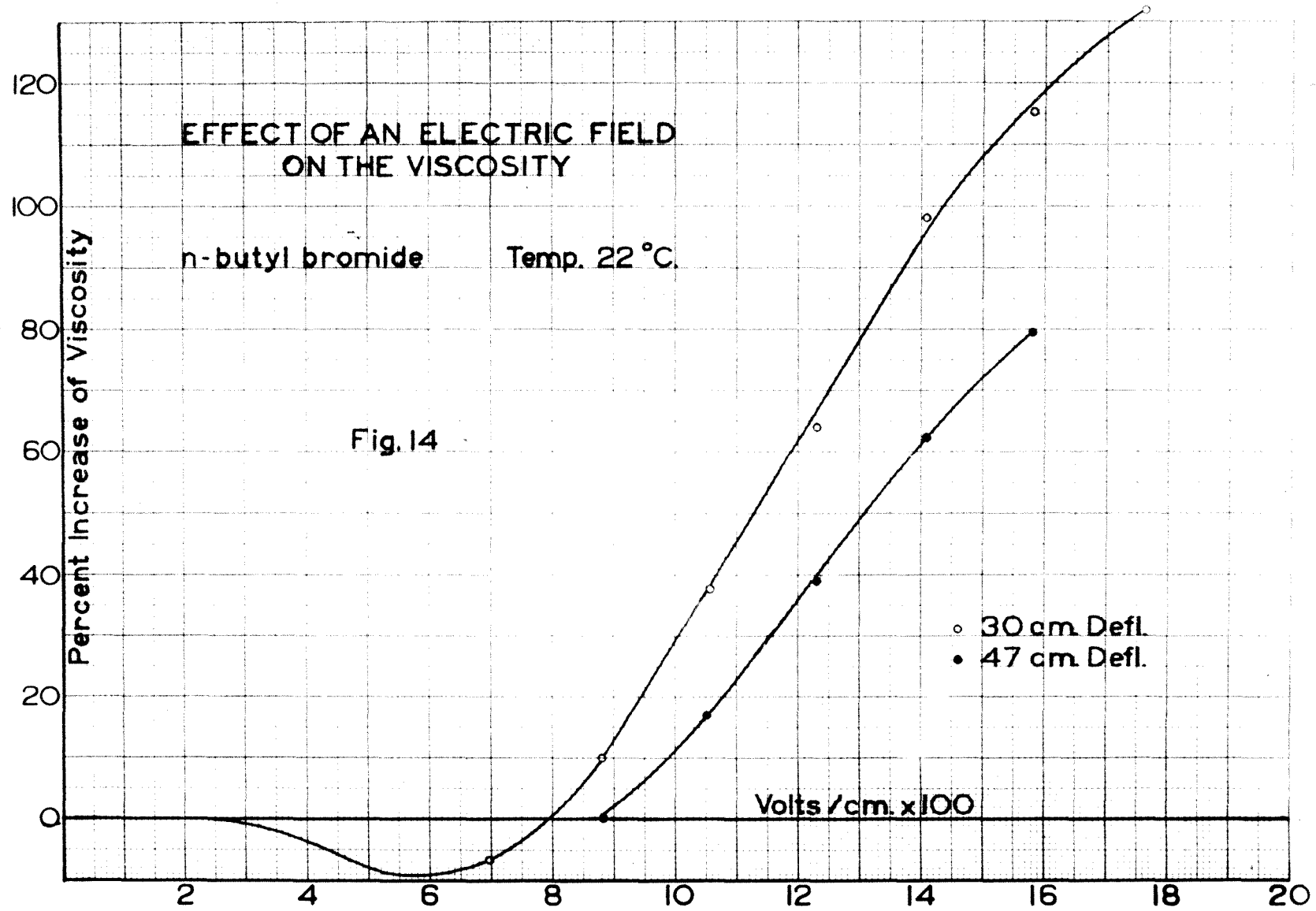

EFFECT OF AN ELECTRIC FIELD
ON THE VISCOSITY
n-butyl bromide
Temp. 22 °C.
Percent Increase of Viscosity
Volts / cm. x 100
30 cm. Defl.
47 cm. Defl.
0
20
40
60
80
100
120
2
4
6
8
10
12
14
16
18
20

Fig. 14

Discussion of Results

The data taken in this investigation are all tabulated in Tables V to XVII. The results are also presented in graphical form in Fig. 7 through Fig. 14. The change in the viscosity is much larger than had been expected when the investigation was undertaken. The dipole moments of the various liquids are given in Table III. The data show that, for a given field strength and a given original deflection of the suspension, the greater the dipole moment the greater will be the percentage change in the viscosity. The deflection of the suspension is a direct measure of the shear transmitted through the liquid and therefore of the viscous stresses existing in the liquid. The data show in every case that as the viscous stress in the liquid increases the percentage change in the viscosity decreases for a given strength of electric field and a given dipole moment. In two cases, namely chloroform and n-butyl bromide, it will be noted that the viscosity tends to decrease at low fields and then to increase as the field strength is increased. The data for Ethyl Acetate and Aniline were not plotted graphically since experimental difficulties prevented the taking of a sufficient

amount of data for a graph to indicate anything. The data for carbontetrachloride and benzene also have not been plotted since in these cases the electric field caused no change in the viscosity. Decalin which has a dipole moment of zero and therefore should not be expected to show any effect due to an electric field, shows a small increase in the viscosity. I attribute this to impurities in the sample which I obtained.

A THEORY OF THE EFFECT OF AN ELECTRIC FIELD ON THE VISCOSITY OF LIQUIDS

If the liquid is one which has a dipole moment, the electric field will tend to orient the molecules of the liquid in a direction which is parallel to the field. If E be the field strength and m the electric dipole moment of the molecule, the energy of the molecule due to the electric field will be $E m \cos\theta$, where θ is the angle between the dipole axis and the electric field. There are also thermal and viscous energies associated with the molecule. Thermal energy does not depend upon any angle, hence will cause no orientation. Viscous stresses, as shown by Raman and Krishnan in their theory of flow birefringence, tends to orient the molecules of the liquid at an angle of 45° to the direction of the flow. This 45° orientation then is the position in which a minimum of shear is transmitted by the liquid, or in other words corresponds to the lowest value of the viscosity. The amount of orientation due to viscous stresses when in equilibrium with thermal energy is proportional to the product of the viscosity and the velocity gradient at the point, and is also dependent on the shape anisotropy of the molecule. If we now place the liquid flow in an electric field, we will then have an equilibrium between the three energies; thermal,

viscous and electric. If the electric field is in a direction other than at 45° to the flow, the equilibrium position will be at some direction other than at 45° to the flow and will cause an increase in the shear which the liquid will transmit. Since the velocity gradient has not changed this means that the viscosity coefficient has changed.

Kuhn has also investigated the equilibrium of an elliptically shaped molecule in a viscous flow. He finds that the molecule is in rotation, the angular velocity, however, is not constant but reaches a minimum when the major axis of the molecule makes an angle of 45° to the direction of flow. Statistically this is the same result that Raman and Krishnan obtain in a different manner. However, here we should notice that the molecule is in actual rotation, not merely oscillating about the 45° position as might be the case in Raman and Krishnan's theory. If we now subject the molecule which has a dipole moment to an electric field, the rotation will cease when the field becomes sufficiently strong. The reason for this is that the dipole moment has a definite direction and the potential energy of the molecule has a minimum at only one angle while the potential energy of the molecule with regard to the viscous forces has a minimum in two positions.

Let us now see what predictions can be made from this simple qualitative theory as to the effect of an electric field upon the viscosity of a liquid. First we can say that if a molecule has no dipole moment the electric field should not affect the viscosity. This agrees with the results from the tests on carbontetrachloride and benzene. Secondly, we can say that the greater the dipole moment, the greater the effect which is checked in general by the experimental results. Third, we can state that the greater the viscous force in the liquid, the less will be the effect of a given field on the viscosity, this is also checked by my experimental results in every case. Fourth, we can state that no appreciable increase in the viscosity can take place until the electric field has stopped the rotation. This also agrees very well with the experimental results, for in general the electric field causes little or no change in the viscosity up to a certain value and then suddenly the viscosity begins to increase when the field is increased.

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BIBLIOGRAPHY

1. A Monograph on Viscometry. Barr. Oxford Univ. Press 1931

2. Viscosity of Liquids. Hatschek. D. Van Nostrand 1928

3. Dielektrische Polarisation. O. Fuchs and K. L. Wolf.
Hand und Jahrbuch der Chemischen Physik 1935

4. Theory of Flowing Birefringence. Raman and Krishnan.
Phil. Mag. 5, 1928, p. 769.

5. Electrostatic Effect on the Viscosity of Fluids.
Herzog, Kudar, and Paersch.
Naturwissenschaften, Sept. 8, 1933, p. 662.

6. Electrostatic Effect on the Viscosity of Fluids.
Herzog, Kudar and Paersch.
Phy. Zeit. 35, June 1, 1934, p. 446.

7. Particle Shape and Size from Viscosity and Flow Double Refraction.
W. Kuhn. Zeit. Phy. Chem. Abt. A, Vol. 161, 1932, p. 1.